Rogier Braakman

Evolutionary Self-organization of Ecosystem Metabolism & the Search for Laws of Life

1
00:00:00,720 --> 00:00:10,759
[Music]

2
00:00:15,959 --> 00:00:13,770
so yes thank you thank you for the

3
00:00:18,480 --> 00:00:15,969
opportunity to talk here and I'm

4
00:00:20,550 --> 00:00:18,490
actually very happy to be following Hong

5
00:00:22,769 --> 00:00:20,560
Yang's a very excellent talk I think it

6
00:00:24,720 --> 00:00:22,779
builds a just a perfect bridge from the

7
00:00:27,420 --> 00:00:24,730
beautiful talks about metabolism and

8
00:00:29,460 --> 00:00:27,430
metabolic pathways this morning towards

9
00:00:32,609 --> 00:00:29,470
the ways in which I would like to think

10
00:00:34,439 --> 00:00:32,619
a little bit about metabolism and I

11
00:00:36,750 --> 00:00:34,449
should mention that I'm gonna be talking

12
00:00:39,689 --> 00:00:36,760
about a story an evolutionary story that

13
00:00:42,539 --> 00:00:39,699

plays out much more recent than origin

14
00:00:44,549 --> 00:00:42,549
so several billion years later but I

15
00:00:46,259 --> 00:00:44,559
think it's very relevant because you

16
00:00:48,090 --> 00:00:46,269
know of course if there are physical

17
00:00:49,979 --> 00:00:48,100
laws physical principles that are

18
00:00:52,439 --> 00:00:49,989
governing the emergence of life they

19
00:00:56,430 --> 00:00:52,449
don't go away once life is there right

20
00:00:57,689 --> 00:00:56,440
and so studying evolution in intractable

21
00:00:59,160 --> 00:00:57,699
systems that are playing out more

22
00:01:03,030 --> 00:00:59,170
recently can actually help us think

23
00:01:05,460 --> 00:01:03,040
about what those principles are and so

24
00:01:06,870 --> 00:01:05,470
you know so we but but in doing that I

25
00:01:08,910 --> 00:01:06,880
think it's important for us to think

26
00:01:10,590 --> 00:01:08,920
about finding the correct sort of

27
00:01:12,990 --> 00:01:10,600
reference frames to be thinking about

28
00:01:15,990 --> 00:01:13,000
evolution that are compatible to asking

29
00:01:17,750 --> 00:01:16,000
how we ask questions about emergence and

30
00:01:20,640 --> 00:01:17,760
so you know in Hong Kong stock talk

31
00:01:21,780 --> 00:01:20,650
focused on ideas of information flow and

32
00:01:24,030 --> 00:01:21,790
how that relates to population dynamics

33
00:01:26,730 --> 00:01:24,040
and I want to sort of talk a little bit

34
00:01:31,890 --> 00:01:26,740
more about mass and energy flows and

35
00:01:36,980 --> 00:01:31,900
sort of at that level so in in my work

36
00:01:40,230 --> 00:01:36,990
in in in general I'm interested in

37
00:01:43,410 --> 00:01:40,240
metabolic evolution I study metabolism

38
00:01:44,460 --> 00:01:43,420

in general and one of the things one of

39
00:01:47,760 --> 00:01:44,470
the most interesting things actually

40
00:01:49,290 --> 00:01:47,770
about metabolism to me is that it's not

41
00:01:51,380 --> 00:01:49,300
just a system but it's actually also a

42
00:01:53,940 --> 00:01:51,390
lens through which we can study

43
00:01:55,590 --> 00:01:53,950
organisms and it's because metabolism

44
00:01:58,410 --> 00:01:55,600
express itself at many different scales

45
00:02:00,690 --> 00:01:58,420
for within living systems so at the

46
00:02:03,090 --> 00:02:00,700
lowest level metabolism is basically

47
00:02:06,149 --> 00:02:03,100
chemical reactions like organic

48
00:02:09,300 --> 00:02:06,159
chemistry catalyzed by small metals and

49
00:02:11,100 --> 00:02:09,310
enzymes and cofactors if we zoom out to

50
00:02:13,110 --> 00:02:11,110
the Seiler level metabolism is now

51
00:02:14,940 --> 00:02:13,120
networks of that kind of chemistry that

52
00:02:17,730 --> 00:02:14,950
cells use to take in their environmental

53
00:02:18,930 --> 00:02:17,740
inputs and recreate themselves if you

54
00:02:20,910 --> 00:02:18,940
keep zooming out to the level of

55
00:02:22,800 --> 00:02:20,920
ecosystem the tablets in manaus network

56
00:02:24,480 --> 00:02:22,810
so that kind of networks where does it

57
00:02:26,160 --> 00:02:24,490
media it's not just the growth of cells

58
00:02:27,660 --> 00:02:26,170
but also the interactions the social

59
00:02:29,910 --> 00:02:27,670
interactions and the trophic exchanges

60
00:02:32,160 --> 00:02:29,920
between cells and if you keep zooming

61
00:02:33,720 --> 00:02:32,170
out at the global scale the metabolic

62
00:02:35,699 --> 00:02:33,730
activity of all cells on earth together

63
00:02:38,250 --> 00:02:35,709

is what's mediating the global elemental

64
00:02:41,520 --> 00:02:38,260
cycles but the key point is that all of

65
00:02:43,080 --> 00:02:41,530
these scales is the same chemistry right

66
00:02:45,270 --> 00:02:43,090
and so metabolism provides kind of a

67
00:02:49,050 --> 00:02:45,280
lens to be thinking about how we link up

68
00:02:51,150 --> 00:02:49,060
things like pathway innovations to

69
00:02:52,470 --> 00:02:51,160
adaptive radiations to be Co system

70
00:02:55,260 --> 00:02:52,480
restructuring and to global

71
00:02:56,250 --> 00:02:55,270
biogeochemical perturbations and the

72
00:02:57,870 --> 00:02:56,260
other thing in there is that because

73
00:03:00,180 --> 00:02:57,880
we're thinking at the level of chemistry

74
00:03:01,320 --> 00:03:00,190
again and this you know comes back to

75
00:03:03,000 --> 00:03:01,330
sort of some of the other themes we've

76
00:03:04,740 --> 00:03:03,010
been talking about before it allows us

77
00:03:07,850 --> 00:03:04,750
to think about metabolic or evolutionary

78
00:03:11,940 --> 00:03:07,860
change in terms of shifts between

79
00:03:13,590 --> 00:03:11,950
regimes of chemical dynamics and sort of

80
00:03:15,949 --> 00:03:13,600
you know in a sort of a physical way of

81
00:03:20,250 --> 00:03:15,959
thinking about evolution in that sense

82
00:03:22,170 --> 00:03:20,260
so the the system I'll be talking about

83
00:03:24,210 --> 00:03:22,180
in trying to build up some of these

84
00:03:27,240 --> 00:03:24,220
ideas you know was introduced by Hong

85
00:03:28,530 --> 00:03:27,250
Kong it's this cyanobacteria that lives

86
00:03:31,800 --> 00:03:28,540
in the surface oceans called

87
00:03:33,930 --> 00:03:31,810
prochlorococcus it's one of the most

88
00:03:38,280 --> 00:03:33,940

abundant cell cell living organisms on

89
00:03:39,810 --> 00:03:38,290
earth you know it lives between sort of

90
00:03:41,550 --> 00:03:39,820
these bands here everywhere out in the

91
00:03:45,150 --> 00:03:41,560
open ocean and form sort of a planet

92
00:03:46,770 --> 00:03:45,160
wrapping population of cells there's you

93
00:03:49,319 --> 00:03:46,780
know several times ten to the twenty

94
00:03:51,960 --> 00:03:49,329
seven of these cells on earth and they

95
00:03:53,610 --> 00:03:51,970
they form a sizeable fraction of primary

96
00:03:55,350 --> 00:03:53,620
productivity and photosynthesis on earth

97
00:03:57,420 --> 00:03:55,360
they're part of what's known as the

98
00:03:58,530 --> 00:03:57,430
marine pico center bacteria where

99
00:04:00,539 --> 00:03:58,540
together with their sister lineage

100
00:04:02,610 --> 00:04:00,549
marine cynical caucus they fix something

101
00:04:05,069 --> 00:04:02,620
like a quarter of all co2 in the oceans

102
00:04:07,440 --> 00:04:05,079
so really it's a it's a cellular system

103
00:04:08,699 --> 00:04:07,450
but it's also a planetary system right

104
00:04:09,930 --> 00:04:08,709
and so when we think about the evolution

105
00:04:11,039 --> 00:04:09,940
of the system it's also interesting to

106
00:04:13,020 --> 00:04:11,049
sort of think about and keep in mind

107
00:04:14,850 --> 00:04:13,030
what happens to the planet where the

108
00:04:17,779 --> 00:04:14,860
system switches on and comes on law

109
00:04:19,800 --> 00:04:17,789
comes on line and Earth history

110
00:04:21,120 --> 00:04:19,810
so there's several things about the

111
00:04:22,980 --> 00:04:21,130
system that make it very appealing for

112
00:04:25,200 --> 00:04:22,990
studying evolution ever studying

113
00:04:28,710 --> 00:04:25,210

metabolism one of the things is that as

114
00:04:30,240 --> 00:04:28,720
I mentioned you know it has very ways in

115
00:04:31,740 --> 00:04:30,250
which its ecology and the relationship

116
00:04:34,140 --> 00:04:31,750
between ecology and phylogeny are very

117
00:04:34,710 --> 00:04:34,150
well understood so if you go out into

118
00:04:35,910 --> 00:04:34,720
the open

119
00:04:37,500 --> 00:04:35,920
motioning you look by depth oh you'll

120
00:04:38,970 --> 00:04:37,510
see is that the population separates

121
00:04:42,000 --> 00:04:38,980
into a sort of layered population

122
00:04:43,560 --> 00:04:42,010
structure where the more the deepest

123
00:04:45,600 --> 00:04:43,570
branching populations live at the bottom

124
00:04:46,980 --> 00:04:45,610
of the euphotic zone where light energy

125
00:04:48,660 --> 00:04:46,990
is low energy concentrations are

126
00:04:51,120 --> 00:04:48,670
elevated whereas the most recent

127
00:04:52,470 --> 00:04:51,130
branching organisms lineages live at the

128
00:04:54,900 --> 00:04:52,480
top where light energy is abundant

129
00:04:55,980 --> 00:04:54,910
nutrient concentrations are low right so

130
00:04:57,810 --> 00:04:55,990
you have this sort of central light

131
00:05:00,000 --> 00:04:57,820
nutrient gradient that organizes the

132
00:05:01,350 --> 00:05:00,010
system and so what I set out to do is to

133
00:05:03,150 --> 00:05:01,360
see how does the metabolism of this

134
00:05:04,530 --> 00:05:03,160
system change along that gradient and

135
00:05:06,990 --> 00:05:04,540
what does that tell us about the

136
00:05:08,580 --> 00:05:07,000
evolution of the system as a whole and a

137
00:05:09,960 --> 00:05:08,590
lot of what I'm talking about you know

138
00:05:12,360 --> 00:05:09,970

is in if you want to read about it in

139
00:05:16,470 --> 00:05:12,370
this paper that came out earlier this

140
00:05:18,780 --> 00:05:16,480
past year right and so to look at this

141
00:05:20,240 --> 00:05:18,790
question I'm thankful to Donato for

142
00:05:23,040 --> 00:05:20,250
already introducing this idea earlier

143
00:05:24,150 --> 00:05:23,050
but so to do that I've you know used

144
00:05:26,240 --> 00:05:24,160
this system which have been trying to

145
00:05:28,770 --> 00:05:26,250
push now for the last several years

146
00:05:30,420 --> 00:05:28,780
where basically you integrate metabolic

147
00:05:31,710 --> 00:05:30,430
Network instructions with phylogenetic

148
00:05:33,990 --> 00:05:31,720
instructions to build trees of

149
00:05:35,580 --> 00:05:34,000
functional metabolic networks so the way

150
00:05:37,500 --> 00:05:35,590
this works is let's say you have some

151
00:05:39,420 --> 00:05:37,510
something Eric that you're interested in

152
00:05:41,250 --> 00:05:39,430
where you know these nodes are molecules

153
00:05:42,570 --> 00:05:41,260
and the links are reactions and in black

154
00:05:44,880 --> 00:05:42,580
are all the parts that are universal so

155
00:05:46,620 --> 00:05:44,890
everyone has them and let's say that you

156
00:05:47,820 --> 00:05:46,630
know that within that clade or in that

157
00:05:50,610 --> 00:05:47,830
that group you're looking at there's

158
00:05:52,409 --> 00:05:50,620
three known alternatives a pink pathway

159
00:05:54,240 --> 00:05:52,419
yellow path in a blue pathway which you

160
00:05:57,090 --> 00:05:54,250
then do is take all the genomes in that

161
00:05:58,830 --> 00:05:57,100
plate or in that phylum and look at the

162
00:06:01,170 --> 00:05:58,840
distribution of the genes encoding those

163
00:06:02,550 --> 00:06:01,180

pathways and so let's say that in you

164
00:06:04,469 --> 00:06:02,560
know in this case you see that the genes

165
00:06:05,940 --> 00:06:04,479
for the yellow pathway are universally

166
00:06:07,290 --> 00:06:05,950
distributed across your tree and across

167
00:06:09,180 --> 00:06:07,300
the roots and that implies that the

168
00:06:11,330 --> 00:06:09,190
yellow path is the ancestral pathway and

169
00:06:13,469 --> 00:06:11,340
that pink and blue were derived from it

170
00:06:15,150 --> 00:06:13,479
there's one additional key constraint

171
00:06:17,219 --> 00:06:15,160
which is that in going from yellow to

172
00:06:18,659 --> 00:06:17,229
say blue the first gained the blue

173
00:06:20,820 --> 00:06:18,669
pathway before you can lose the yellow

174
00:06:22,710 --> 00:06:20,830
pathway because you at first you lose

175
00:06:24,500 --> 00:06:22,720
the yellow pathway flows through the

176
00:06:26,640 --> 00:06:24,510
network is cut and the lineage dies off

177
00:06:29,010 --> 00:06:26,650
right and so what this then means is

178
00:06:30,240 --> 00:06:29,020
that you have now tree of phenotypes so

179
00:06:31,830 --> 00:06:30,250
these are all functional metabolic

180
00:06:33,030 --> 00:06:31,840
networks what you can do is you can

181
00:06:34,710 --> 00:06:33,040
start looking at the biochemical

182
00:06:36,540 --> 00:06:34,720
properties of the individual pathways to

183
00:06:38,640 --> 00:06:36,550
try to understand what drove the system

184
00:06:40,770 --> 00:06:38,650
from one state to another one so for

185
00:06:42,540 --> 00:06:40,780
example looking at differences in trace

186
00:06:44,400 --> 00:06:42,550
metal usages of the enzymes

187
00:06:46,080 --> 00:06:44,410
maybe there's oxygen sensitivities and

188
00:06:47,810 --> 00:06:46,090

the different enzymes maybe there's

189
00:06:49,640 --> 00:06:47,820
differences in ATP usages

190
00:06:50,780 --> 00:06:49,650
- in different pathways and by making

191
00:06:52,670 --> 00:06:50,790
these kind of comparison you can start

192
00:06:55,760 --> 00:06:52,680
to infer what was the evolutionary

193
00:06:57,640 --> 00:06:55,770
driving mechanism so taking this kind of

194
00:07:00,170 --> 00:06:57,650
approach and looking at prochlorococcus

195
00:07:02,210 --> 00:07:00,180
you see something very dramatic actually

196
00:07:04,310 --> 00:07:02,220
happens so what I've shown here is the

197
00:07:05,900 --> 00:07:04,320
metabolic core so this is the

198
00:07:07,510 --> 00:07:05,910
photosynthetic electron transport chain

199
00:07:10,070 --> 00:07:07,520
and this core carbohydrate metabolism

200
00:07:11,780 --> 00:07:10,080
this is where electrons and Co to come

201
00:07:13,970 --> 00:07:11,790
together to initiate all of biosynthesis

202
00:07:14,930 --> 00:07:13,980
and what happens actually in this part

203
00:07:16,640 --> 00:07:14,940
of the network is that you see the

204
00:07:17,990 --> 00:07:16,650
prochlorococcus forms of very unique

205
00:07:18,740 --> 00:07:18,000
lineages within the rest of

206
00:07:20,750 --> 00:07:18,750
cyanobacteria

207
00:07:23,600 --> 00:07:20,760
the whole metabolic core undergoes

208
00:07:25,640 --> 00:07:23,610
remodeling any way that is uncommon in

209
00:07:27,410 --> 00:07:25,650
the rest of santé bacteria so almost

210
00:07:29,630 --> 00:07:27,420
everything undergoes change you see path

211
00:07:31,850 --> 00:07:29,640
genes are being lost genes are being

212
00:07:33,080 --> 00:07:31,860
gained the stoichiometry is in the

213
00:07:35,140 --> 00:07:33,090

pigments of the photo systems are

214
00:07:37,460 --> 00:07:35,150
undergoing change so a lot is happening

215
00:07:38,900 --> 00:07:37,470
which already is telling you a lot right

216
00:07:40,520 --> 00:07:38,910
because this is where everything starts

217
00:07:42,740 --> 00:07:40,530
so change is not going to be easy

218
00:07:45,140 --> 00:07:42,750
so if you see change it's suggesting of

219
00:07:46,760 --> 00:07:45,150
a strong driving force and the other

220
00:07:48,950 --> 00:07:46,770
thing that we see as part of this change

221
00:07:50,600 --> 00:07:48,960
sort of surprisingly initially is that

222
00:07:53,090 --> 00:07:50,610
it seems to be adding what looked like

223
00:07:54,830 --> 00:07:53,100
electron drains in the network right so

224
00:07:57,110 --> 00:07:54,840
as system is evolving networks are being

225
00:07:59,090 --> 00:07:57,120
interrupted and it looks like Panthers

226
00:08:02,530 --> 00:07:59,100
are being added for excreting small

227
00:08:04,820 --> 00:08:02,540
organic carbon molecules out of the cell

228
00:08:07,070 --> 00:08:04,830
now that seems kind of like a surprising

229
00:08:09,290 --> 00:08:07,080
thing why would a assist to be evolving

230
00:08:11,660 --> 00:08:09,300
to burn energy out into the environment

231
00:08:14,330 --> 00:08:11,670
in that sense and so to try to make

232
00:08:15,860 --> 00:08:14,340
sense of this I took the information we

233
00:08:17,060 --> 00:08:15,870
know from metabolism and try to

234
00:08:19,160 --> 00:08:17,070
integrate it with everything else we

235
00:08:21,400 --> 00:08:19,170
know about the system so looking at the

236
00:08:23,930 --> 00:08:21,410
population structure genome evolution

237
00:08:26,030 --> 00:08:23,940
proteome evolution growth rate light

238
00:08:28,280 --> 00:08:26,040

physiology everything else that you know

239
00:08:29,450 --> 00:08:28,290
we can find and when you do that when

240
00:08:31,070 --> 00:08:29,460
you integrate all that information

241
00:08:32,750 --> 00:08:31,080
together it turns out that you can

242
00:08:35,000 --> 00:08:32,760
actually align all of the macroscale

243
00:08:37,670 --> 00:08:35,010
diversity within this system along a

244
00:08:40,070 --> 00:08:37,680
single physiological axis which is

245
00:08:42,100 --> 00:08:40,080
suggesting that over geologic time the

246
00:08:44,540 --> 00:08:42,110
system evolution is sort of steadily

247
00:08:47,060 --> 00:08:44,550
maximizing this one single physiological

248
00:08:48,830 --> 00:08:47,070
parameter which is the ratio of electron

249
00:08:51,080 --> 00:08:48,840
flux to the nutrient flux in the cell

250
00:08:52,580 --> 00:08:51,090
let me unpack that a little bit electron

251
00:08:54,110 --> 00:08:52,590
flux is just light intensity times

252
00:08:56,300 --> 00:08:54,120
absorption cross section times quantum

253
00:08:58,340 --> 00:08:56,310
efficiency and nutrient flux is the

254
00:09:00,890 --> 00:08:58,350
growth rate times the nutrient quota the

255
00:09:01,700 --> 00:09:00,900
number of atoms in a Cell and so you

256
00:09:04,130 --> 00:09:01,710
know I already mentioned

257
00:09:05,870 --> 00:09:04,140
you see this light level differentiation

258
00:09:08,150 --> 00:09:05,880
here so these see more light than these

259
00:09:10,070 --> 00:09:08,160
so that's you know driving an increase

260
00:09:11,990 --> 00:09:10,080
in electron flux but at the same time

261
00:09:13,280 --> 00:09:12,000
the the photosynthetic machinery is also

262
00:09:14,660 --> 00:09:13,290
undergoing change in a way that

263
00:09:17,150 --> 00:09:14,670

increases the absorption cross-section

264
00:09:19,670 --> 00:09:17,160
of the cells so the the the the

265
00:09:21,320 --> 00:09:19,680
stoichiometry and the pigments of the

266
00:09:23,390 --> 00:09:21,330
photo systems are being modified in such

267
00:09:25,190 --> 00:09:23,400
a way that they're also absorbing more

268
00:09:28,010 --> 00:09:25,200
of the light that they see of the blue

269
00:09:29,420 --> 00:09:28,020
the blue light and at the same time we

270
00:09:31,610 --> 00:09:29,430
see that the nutrient flux is steadily

271
00:09:33,320 --> 00:09:31,620
going down in this lineage so you see

272
00:09:35,660 --> 00:09:33,330
that the cells are getting smaller the

273
00:09:38,030 --> 00:09:35,670
membranes are going from phospholipid to

274
00:09:39,500 --> 00:09:38,040
sulfa lipids the genome and the proteome

275
00:09:41,990 --> 00:09:39,510
is streamlined in ways that save

276
00:09:44,150 --> 00:09:42,000
nitrogen and phosphorus as well and the

277
00:09:45,470 --> 00:09:44,160
changes to the the photostatic machinery

278
00:09:48,110 --> 00:09:45,480
and the metabolic network end up saving

279
00:09:50,150 --> 00:09:48,120
iron as well so what in fact we were

280
00:09:52,460 --> 00:09:50,160
seeing in the addition of these carbon

281
00:09:54,230 --> 00:09:52,470
excretion pathways is reflective of a

282
00:09:56,270 --> 00:09:54,240
more general process which is increasing

283
00:10:00,200 --> 00:09:56,280
the through flow of electrons through

284
00:10:01,790 --> 00:10:00,210
the system and sort of as a byproduct of

285
00:10:03,470 --> 00:10:01,800
that then ends up excreting some of

286
00:10:06,680 --> 00:10:03,480
these electrons into the into the

287
00:10:10,580 --> 00:10:06,690
environment now try to ask what that

288
00:10:11,900 --> 00:10:10,590

means right so what electrons do is they

289
00:10:14,750 --> 00:10:11,910
transfer energy from the environment

290
00:10:16,220 --> 00:10:14,760
into the cell so in fact what this is

291
00:10:17,270 --> 00:10:16,230
suggesting is that what's going on here

292
00:10:19,940 --> 00:10:17,280
is that evolution is steadily increasing

293
00:10:21,320 --> 00:10:19,950
metabolic rate of the cell and so the

294
00:10:22,610 --> 00:10:21,330
question then becomes why should

295
00:10:24,500 --> 00:10:22,620
evolution increased elie increased

296
00:10:28,580 --> 00:10:24,510
metabolic rate and excretion of organic

297
00:10:30,560 --> 00:10:28,590
carbon and so there's a couple of

298
00:10:32,990 --> 00:10:30,570
additional clues about the system that

299
00:10:33,800 --> 00:10:33,000
you know will help us understand why

300
00:10:35,720 --> 00:10:33,810
this might be

301
00:10:37,400 --> 00:10:35,730
and the main one here is that this

302
00:10:40,460 --> 00:10:37,410
highest metabolic rate phenotype

303
00:10:42,470 --> 00:10:40,470
actually lives in the highest surface

304
00:10:44,540 --> 00:10:42,480
layers environment where the light

305
00:10:46,550 --> 00:10:44,550
energy is most abundant and the nutrient

306
00:10:47,780 --> 00:10:46,560
concentrations are the lowest right so

307
00:10:50,590 --> 00:10:47,790
it suggests that there's a link between

308
00:10:52,850 --> 00:10:50,600
metabolic rate and nutrient acquisition

309
00:10:54,740 --> 00:10:52,860
and that's basically what we ended up

310
00:10:56,270 --> 00:10:54,750
arguing in in the paper which is that

311
00:10:59,330 --> 00:10:56,280
what's going on here is that evolution

312
00:11:01,370 --> 00:10:59,340
is reducing and as an ever more powerful

313
00:11:03,710 --> 00:11:01,380

vacuum cleaner if you will for sucking

314
00:11:05,870 --> 00:11:03,720
up the recalcitrant nutrients from the

315
00:11:07,940 --> 00:11:05,880
environment and as a sort of byproduct

316
00:11:09,680 --> 00:11:07,950
of that sort of exhaust of this more

317
00:11:12,860 --> 00:11:09,690
powerful engine excreting small organic

318
00:11:15,360 --> 00:11:12,870
molecules into the environment we

319
00:11:16,980 --> 00:11:15,370
formalize that a little bit more but

320
00:11:18,900 --> 00:11:16,990
making reversible Michaelis Menten

321
00:11:21,510 --> 00:11:18,910
enzyme kinetics and rewriting it in

322
00:11:22,800 --> 00:11:21,520
terms of nutrient concentrations and for

323
00:11:24,960 --> 00:11:22,810
those of you familiar with resource

324
00:11:27,500 --> 00:11:24,970
ratio theory from ecology it's sort of

325
00:11:30,269 --> 00:11:27,510
an extension of that to geologic time

326
00:11:31,980 --> 00:11:30,279
and when you do that then so now you see

327
00:11:34,230 --> 00:11:31,990
some of the terms we saw before the

328
00:11:35,550 --> 00:11:34,240
nutrient flux is the electron flux this

329
00:11:37,950 --> 00:11:35,560
is the efficiency of carbon fixation

330
00:11:39,780 --> 00:11:37,960
which then gives you the carbon flux the

331
00:11:41,970 --> 00:11:39,790
fraction of exterior carbon here in beta

332
00:11:43,530 --> 00:11:41,980
and the Delta G here is the free energy

333
00:11:47,250 --> 00:11:43,540
of the new update reaction what you can

334
00:11:49,110 --> 00:11:47,260
do is ask if selection is acting now on

335
00:11:51,390 --> 00:11:49,120
the nutrient concentration of the

336
00:11:52,980 --> 00:11:51,400
population at which they live favoring

337
00:11:55,110 --> 00:11:52,990
populations that can grow with lower

338
00:11:57,230 --> 00:11:55,120

nutrient concentrations what sort of

339
00:11:59,460 --> 00:11:57,240
cellular features will start to emerge

340
00:12:00,750 --> 00:11:59,470
and so you can see very quickly that

341
00:12:02,220 --> 00:12:00,760
what you would want to do is you would

342
00:12:04,170 --> 00:12:02,230
lower your nutrient your nutrient

343
00:12:06,329 --> 00:12:04,180
flux which is what we see happening in

344
00:12:08,310 --> 00:12:06,339
the system but a key point here is that

345
00:12:09,630 --> 00:12:08,320
as the nutrient concentrations drop and

346
00:12:11,790 --> 00:12:09,640
cells figure out way to grow at lower

347
00:12:13,380 --> 00:12:11,800
nutrient concentrations the free energy

348
00:12:15,180 --> 00:12:13,390
cost of the nutrient uptake reaction

349
00:12:17,130 --> 00:12:15,190
actually goes up so it becomes more

350
00:12:18,630 --> 00:12:17,140
thermodynamically uphill and so

351
00:12:19,949 --> 00:12:18,640
basically what I think is a good way of

352
00:12:22,560 --> 00:12:19,959
thinking about what the system is then

353
00:12:24,720 --> 00:12:22,570
telling us is that the way it sort of

354
00:12:26,790 --> 00:12:24,730
solves that problem is by driving using

355
00:12:29,190 --> 00:12:26,800
these excess electrons to drive the

356
00:12:31,829 --> 00:12:29,200
system into saturation and coupling that

357
00:12:34,560 --> 00:12:31,839
saturated state metabolism to that

358
00:12:36,210 --> 00:12:34,570
uphill a nutrient uptake reaction but

359
00:12:37,860 --> 00:12:36,220
that brings along with it a lot of extra

360
00:12:39,750 --> 00:12:37,870
carbon that the cell doesn't need and in

361
00:12:41,850 --> 00:12:39,760
fact it wants less of it and so the

362
00:12:44,640 --> 00:12:41,860
excreted carbon allows it to keep

363
00:12:46,410 --> 00:12:44,650

increasing this term of up here without

364
00:12:47,940 --> 00:12:46,420
increasing the overall parameter because

365
00:12:49,740 --> 00:12:47,950
it's actually kind of productive to

366
00:12:51,810 --> 00:12:49,750
increase this term so if you increase

367
00:12:53,130 --> 00:12:51,820
both the electron flux and the expiry of

368
00:12:56,579 --> 00:12:53,140
carbon fraction you can actually solve

369
00:13:00,660 --> 00:12:56,589
the whole problem then so what are the

370
00:13:03,300 --> 00:13:00,670
implications of this framework well it

371
00:13:05,880 --> 00:13:03,310
has a few things and the first thing

372
00:13:07,680 --> 00:13:05,890
that it says is that if you look at this

373
00:13:09,810 --> 00:13:07,690
you know population structure that we

374
00:13:11,370 --> 00:13:09,820
see in the excellent oceans implication

375
00:13:13,740 --> 00:13:11,380
is that the way that that came about is

376
00:13:15,120 --> 00:13:13,750
that you're at a sequence of innovations

377
00:13:17,519 --> 00:13:15,130
near the surface where an assessor

378
00:13:19,140 --> 00:13:17,529
ecotype was living in in a steady-state

379
00:13:20,910 --> 00:13:19,150
equilibrium with its environment an

380
00:13:22,860 --> 00:13:20,920
innovation comes in that enhances the

381
00:13:24,329 --> 00:13:22,870
energy flow through the system that

382
00:13:26,880 --> 00:13:24,339
begins to draw down the nutrient

383
00:13:28,380 --> 00:13:26,890
concentrations in the surface and then

384
00:13:30,570 --> 00:13:28,390
allowing a new

385
00:13:32,670 --> 00:13:30,580
to start expanding in and as the

386
00:13:34,440 --> 00:13:32,680
nutrient concentrations drop is in such

387
00:13:35,820 --> 00:13:34,450
eco type which was adapted to higher

388
00:13:37,950 --> 00:13:35,830

energy concentrations become restricted

389
00:13:39,480 --> 00:13:37,960
further than the wall or water column so

390
00:13:42,270 --> 00:13:39,490
basically evolution is sort of steadily

391
00:13:44,160 --> 00:13:42,280
bending this nutrient curve further and

392
00:13:45,630 --> 00:13:44,170
further down and compressing this

393
00:13:49,260 --> 00:13:45,640
population structure further and further

394
00:13:51,060 --> 00:13:49,270
down the water column what this also

395
00:13:53,280 --> 00:13:51,070
means then is that the implication of

396
00:13:55,170 --> 00:13:53,290
this is that prochlorococcus and you

397
00:13:57,990 --> 00:13:55,180
know on the file plan fin as well have a

398
00:13:59,010 --> 00:13:58,000
important role in shaping the chemistry

399
00:14:01,290 --> 00:13:59,020
in the in the extant

400
00:14:02,880 --> 00:14:01,300
oceans and indeed if you look at

401
00:14:05,130 --> 00:14:02,890
prochlorococcus distributions what you

402
00:14:07,290 --> 00:14:05,140
will see and this is from a transect

403
00:14:09,780 --> 00:14:07,300
your ship going across the whole

404
00:14:11,070 --> 00:14:09,790
atlantic is that and this is depth on

405
00:14:13,440 --> 00:14:11,080
this axis here what you'll see is that

406
00:14:15,900 --> 00:14:13,450
the prochlorococcus populations sort of

407
00:14:17,130 --> 00:14:15,910
retrace the nutrient minima right so

408
00:14:19,080 --> 00:14:17,140
everywhere from core caucuses the

409
00:14:20,220 --> 00:14:19,090
nutrient concentrations are lowest but

410
00:14:21,330 --> 00:14:20,230
it turns out that that's also the

411
00:14:23,820 --> 00:14:21,340
environment where the dissolved organic

412
00:14:25,680 --> 00:14:23,830
carbon levels are at their highest

413
00:14:27,270 --> 00:14:25,690

so dissolved organic carbon in the

414
00:14:29,910 --> 00:14:27,280
global ocean is everywhere sort of at

415
00:14:32,220 --> 00:14:29,920
around 40 micro molar except exactly in

416
00:14:33,780 --> 00:14:32,230
these drops subtropical service oceans

417
00:14:36,540 --> 00:14:33,790
where the concentration spikes up to 80

418
00:14:38,070 --> 00:14:36,550
or 100 micro molar now this of course

419
00:14:40,680 --> 00:14:38,080
has all kinds of implications for

420
00:14:42,300 --> 00:14:40,690
evolution at the ecosystem level right -

421
00:14:43,920 --> 00:14:42,310
both the drawdown of the nutrients dry

422
00:14:46,230 --> 00:14:43,930
as evolution and others but also the

423
00:14:48,750 --> 00:14:46,240
exclusion of organic carbon and to look

424
00:14:51,480 --> 00:14:48,760
at the impacts of that secondary step I

425
00:14:53,910 --> 00:14:51,490
looked at what happens in the metabolism

426
00:14:56,630 --> 00:14:53,920
of SAR 11 which is the most abundant

427
00:14:58,800 --> 00:14:56,640
heterotroph on the planet co-occurs with

428
00:15:00,870 --> 00:14:58,810
prochlorococcus in these environments

429
00:15:02,310 --> 00:15:00,880
and it's in fact almost a little bit

430
00:15:04,080 --> 00:15:02,320
more abundant prochlorococcus globally

431
00:15:06,000 --> 00:15:04,090
but they co-occur always in the same

432
00:15:07,770 --> 00:15:06,010
environment and if you do this kind of

433
00:15:09,930 --> 00:15:07,780
same sort of analysis that I did for

434
00:15:11,850 --> 00:15:09,940
prochlorococcus for SAR 11 what you'll

435
00:15:13,890 --> 00:15:11,860
see that again it's its metabolic core

436
00:15:16,140 --> 00:15:13,900
undergoes a global reorganization

437
00:15:18,420 --> 00:15:16,150
pathways being gained and lost and if

438
00:15:19,770 --> 00:15:18,430

you if you map that diversity on to its

439
00:15:21,810 --> 00:15:19,780
phylogeny what you'll see is that the

440
00:15:23,430 --> 00:15:21,820
metabolic core changes in a way that's

441
00:15:25,410 --> 00:15:23,440
complementary to that of prochlorococcus

442
00:15:27,090 --> 00:15:25,420
so all the pathways that emerges

443
00:15:29,580 --> 00:15:27,100
excretion pathways in prochlorococcus

444
00:15:31,890 --> 00:15:29,590
emerges uptake pathways and SAR 11 and

445
00:15:33,060 --> 00:15:31,900
there's also an excretion pathway that

446
00:15:34,710 --> 00:15:33,070
emerges in started I've been matching an

447
00:15:36,690 --> 00:15:34,720
uptake pathway in prochlorococcus

448
00:15:38,370 --> 00:15:36,700
they've kind of an emergence of free

449
00:15:40,950 --> 00:15:38,380
living mutualism between the two that

450
00:15:42,150 --> 00:15:40,960
you can start to see it even gets a

451
00:15:44,100 --> 00:15:42,160
little bit more interesting than that

452
00:15:46,110 --> 00:15:44,110
because if you look at the metabolic

453
00:15:47,550 --> 00:15:46,120
organization in this system and how

454
00:15:49,430 --> 00:15:47,560
prochlorococcus and started having

455
00:15:51,480 --> 00:15:49,440
interact and you compare that with how

456
00:15:53,610 --> 00:15:51,490
metabolism is distributed across the

457
00:15:54,990 --> 00:15:53,620
organelles of plant cells what you'll

458
00:15:57,990 --> 00:15:55,000
see is that they look like almost exact

459
00:15:59,639 --> 00:15:58,000
analogs of one another so up here is the

460
00:16:01,650 --> 00:15:59,649
ocean microbe community and down here

461
00:16:03,960 --> 00:16:01,660
are plant cells and what you'll see is

462
00:16:05,249 --> 00:16:03,970
that basically the same pathways that

463
00:16:07,769 --> 00:16:05,259

are being used for electron exchange

464
00:16:09,119 --> 00:16:07,779
between prochlorococcus and star 11 look

465
00:16:10,829 --> 00:16:09,129
very similar to the pathways that

466
00:16:13,470 --> 00:16:10,839
chloroplasts and mitochondria use to

467
00:16:15,179 --> 00:16:13,480
exchange electrons so in both cases we

468
00:16:16,980 --> 00:16:15,189
see intermediates of lower glycolysis

469
00:16:18,030 --> 00:16:16,990
and photorespiration sending electrons

470
00:16:19,800 --> 00:16:18,040
from the autotrophic to the

471
00:16:21,240 --> 00:16:19,810
heterotrophic side and in both cases

472
00:16:22,710 --> 00:16:21,250
intermediate from the citric acid cycle

473
00:16:25,019 --> 00:16:22,720
allow electron flow in the opposite

474
00:16:27,780 --> 00:16:25,029
direction but there are a lot more other

475
00:16:29,790 --> 00:16:27,790
similarities beyond that so for example

476
00:16:31,290 --> 00:16:29,800
it's known in ocean communities that you

477
00:16:32,939 --> 00:16:31,300
know prochlorococcus and some star 11

478
00:16:35,009 --> 00:16:32,949
have given up the ability to detoxify

479
00:16:37,949 --> 00:16:35,019
peroxide which is a byproduct of

480
00:16:39,569 --> 00:16:37,959
photosynthesis relying on co-occurring

481
00:16:42,090 --> 00:16:39,579
heterotrophs that do that function for

482
00:16:43,590 --> 00:16:42,100
them same thing in plant cells the

483
00:16:45,569 --> 00:16:43,600
chloroplasts and mitochondria don't do

484
00:16:47,249 --> 00:16:45,579
the the peroxidase reaction to the

485
00:16:49,590 --> 00:16:47,259
peroxide of translation direction itself

486
00:16:51,749 --> 00:16:49,600
that's done by the peroxisome you look

487
00:16:53,100 --> 00:16:51,759
at other enzymes or other genes within

488
00:16:54,749 --> 00:16:53,110

the photo cycle electron transport

489
00:16:56,340 --> 00:16:54,759
chains of actually the electron

490
00:17:00,030 --> 00:16:56,350
transport chains on both sides of the

491
00:17:01,559 --> 00:17:00,040
equation you see that the same genes are

492
00:17:03,780 --> 00:17:01,569
being added to the electron train

493
00:17:05,340 --> 00:17:03,790
transports in both systems that are

494
00:17:07,890 --> 00:17:05,350
draining electrons from the electron

495
00:17:09,809 --> 00:17:07,900
transport chain in both cases the same

496
00:17:11,549 --> 00:17:09,819
genes are being added if you look at the

497
00:17:12,720 --> 00:17:11,559
photosystems themselves and the first

498
00:17:14,909 --> 00:17:12,730
tech electron transport chains

499
00:17:16,470 --> 00:17:14,919
themselves you see below Karakas is

500
00:17:18,329 --> 00:17:16,480
somewhat unique amongst anti-bacterial

501
00:17:20,549 --> 00:17:18,339
for having chlorophyll a and B it has a

502
00:17:23,399 --> 00:17:20,559
tweak so geometry if it's photosystem 2

503
00:17:25,409 --> 00:17:23,409
to one it uses different pigments in a

504
00:17:26,720 --> 00:17:25,419
and B as I mentioned and all those

505
00:17:29,430 --> 00:17:26,730
features are similar to what plant

506
00:17:32,130 --> 00:17:29,440
chloroplasts do as well so if you zoom

507
00:17:33,690 --> 00:17:32,140
out then to this kind of eagle eye view

508
00:17:35,789 --> 00:17:33,700
of this and focusing on the metabolism

509
00:17:38,250 --> 00:17:35,799
it really kind of starts to look as if

510
00:17:40,409 --> 00:17:38,260
the global ocean in the in the tropical

511
00:17:41,930 --> 00:17:40,419
and sub-tropical surface oceans these

512
00:17:44,010 --> 00:17:41,940
communities are essentially

513
00:17:45,810 --> 00:17:44,020

free-floating chloroplasts and

514
00:17:47,190 --> 00:17:45,820
mitochondria sort of interacting with

515
00:17:49,770 --> 00:17:47,200
each other just like organelles and

516
00:17:52,080 --> 00:17:49,780
plant cells do or alternatively that a

517
00:17:55,500 --> 00:17:52,090
plant cells like a microscopic microbial

518
00:17:56,970 --> 00:17:55,510
ocean recapitulated cell

519
00:17:59,370 --> 00:17:56,980
but I think it also allows us to think

520
00:18:01,860 --> 00:17:59,380
about mutualism in a slightly different

521
00:18:03,900 --> 00:18:01,870
way because what these electron exchange

522
00:18:05,810 --> 00:18:03,910
pathways are doing is that what was

523
00:18:08,880 --> 00:18:05,820
initially otherwise going to be

524
00:18:10,860 --> 00:18:08,890
metabolic waste energetic waste now

525
00:18:13,770 --> 00:18:10,870
these exchange pathways are essentially

526
00:18:15,900 --> 00:18:13,780
recycling those electrons allowing the

527
00:18:20,820 --> 00:18:15,910
maximization of electron flux to proceed

528
00:18:24,270 --> 00:18:20,830
now at the community level where as the

529
00:18:26,220 --> 00:18:24,280
loss of these peroxide the toxification

530
00:18:27,720 --> 00:18:26,230
genes and the abundant components of the

531
00:18:29,490 --> 00:18:27,730
system and restricting them to the less

532
00:18:31,170 --> 00:18:29,500
abundant ones and the key point here is

533
00:18:33,810 --> 00:18:31,180
that these genes involve iron in their

534
00:18:36,630 --> 00:18:33,820
active site lowers the average iron flux

535
00:18:38,190 --> 00:18:36,640
of the of the components and so what I

536
00:18:40,530 --> 00:18:38,200
think this is saying is that in many

537
00:18:43,230 --> 00:18:40,540
ways mutualisms are sort of like a self

538
00:18:45,600 --> 00:18:43,240

amplifying feedback loop that that

539
00:18:47,850 --> 00:18:45,610
maximized the electron to nutrient flux

540
00:18:49,590 --> 00:18:47,860
at the ecosystem level sort of emerging

541
00:18:52,980 --> 00:18:49,600
from that same Drive operating at the

542
00:18:54,750 --> 00:18:52,990
lower level of organization so kind of

543
00:18:56,730 --> 00:18:54,760
coming back then sort of and zooming out

544
00:18:58,260 --> 00:18:56,740
to the to a sort of more general level

545
00:18:59,820 --> 00:18:58,270
but I think this is telling us then is

546
00:19:02,970 --> 00:18:59,830
that at the ecosystem level the way

547
00:19:04,790 --> 00:19:02,980
evolution operates is that ecosystems as

548
00:19:07,080 --> 00:19:04,800
a whole follow these sort of self

549
00:19:09,000 --> 00:19:07,090
amplifying and self-organizing

550
00:19:11,130 --> 00:19:09,010
evolutionary trajectories where

551
00:19:13,260 --> 00:19:11,140
innovations that increase the energy

552
00:19:14,880 --> 00:19:13,270
input into the system caused a drawdown

553
00:19:17,130 --> 00:19:14,890
of nutrients in the environment and an

554
00:19:19,530 --> 00:19:17,140
increase in this in the biomass tanning

555
00:19:21,420 --> 00:19:19,540
stock of the ecosystem but this is done

556
00:19:23,490 --> 00:19:21,430
by increasing the electron flux faster

557
00:19:25,860 --> 00:19:23,500
than the nutrient flux and so you have

558
00:19:27,330 --> 00:19:25,870
an increased amount of excess electrons

559
00:19:29,310 --> 00:19:27,340
sort of circulating through the system

560
00:19:31,020 --> 00:19:29,320
and those excess electrons then drive

561
00:19:32,130 --> 00:19:31,030
the organization and the emergence of

562
00:19:35,250 --> 00:19:32,140
higher levels of organization that

563
00:19:36,810 --> 00:19:35,260

continue that same sort of process and

564
00:19:38,400 --> 00:19:36,820
so the key point then is that if you

565
00:19:40,950 --> 00:19:38,410
look I think what this is saying is that

566
00:19:43,620 --> 00:19:40,960
if you look at evolution on geologic

567
00:19:45,480 --> 00:19:43,630
timescales it's not actually a zero-sum

568
00:19:48,090 --> 00:19:45,490
game is that what it's doing is it's

569
00:19:51,930 --> 00:19:48,100
promoting a more energetic or more

570
00:19:53,640 --> 00:19:51,940
massive and a more complex biosphere now

571
00:19:55,770 --> 00:19:53,650
this has then implications for thinking

572
00:19:57,840 --> 00:19:55,780
about Earth history as a whole so if you

573
00:20:00,600 --> 00:19:57,850
think but you know where oxygen in our

574
00:20:02,690 --> 00:20:00,610
atmosphere comes from this is sort of a

575
00:20:04,230 --> 00:20:02,700
simplified view of the carbon cycle

576
00:20:06,150 --> 00:20:04,240
photosynthesis balanced against

577
00:20:08,550 --> 00:20:06,160
respiration now of course this is

578
00:20:09,450 --> 00:20:08,560
ultimately the source of the oxygen but

579
00:20:10,740 --> 00:20:09,460
if these two process

580
00:20:13,470 --> 00:20:10,750
these are perfectly balanced you won't

581
00:20:15,840 --> 00:20:13,480
actually have free oxygen so you know

582
00:20:17,460 --> 00:20:15,850
for long over long timescales of history

583
00:20:18,840 --> 00:20:17,470
it's thought that the way we accumulate

584
00:20:21,389 --> 00:20:18,850
atmosphere and the oxygen is that a

585
00:20:23,630 --> 00:20:21,399
small fraction of that carbon ends up

586
00:20:26,580 --> 00:20:23,640
being buried inside of the Earth's crust

587
00:20:28,230 --> 00:20:26,590
so if you now think about this on top of

588
00:20:29,880 --> 00:20:28,240

this kind of evolutionary dynamic where

589
00:20:31,649 --> 00:20:29,890
you have these innovations that increase

590
00:20:33,930 --> 00:20:31,659
the global standing stock of organic

591
00:20:36,029 --> 00:20:33,940
carbon and you have sort of always a

592
00:20:38,250 --> 00:20:36,039
steady background burial rate of 0.1

593
00:20:40,049 --> 00:20:38,260
percent or so if you suddenly increase

594
00:20:42,029 --> 00:20:40,059
the total standing soft organic carbon

595
00:20:43,680 --> 00:20:42,039
and this relative flux increases the

596
00:20:47,700 --> 00:20:43,690
total absolute flux of organic carbon

597
00:20:50,450 --> 00:20:47,710
burial now so turns out that if you look

598
00:20:52,980 --> 00:20:50,460
at molecular clock analyses that

599
00:20:54,630 --> 00:20:52,990
prochlorococcus and the Marine Pico

600
00:20:56,730 --> 00:20:54,640
Center bacteria in fact all planktonic

601
00:20:58,440 --> 00:20:56,740
santé bacteria emerge sort of right

602
00:21:00,269 --> 00:20:58,450
around this time in the earth history

603
00:21:02,610 --> 00:21:00,279
here between half a billion and about a

604
00:21:04,680 --> 00:21:02,620
billion years ago when oxygen starts to

605
00:21:08,070 --> 00:21:04,690
rise in the atmosphere so down here just

606
00:21:10,080 --> 00:21:08,080
as a bit more general point this is sort

607
00:21:12,299 --> 00:21:10,090
of like a general view of the history of

608
00:21:14,669 --> 00:21:12,309
the earth oxygenation and you know a lot

609
00:21:17,100 --> 00:21:14,679
of people often focus on the great

610
00:21:18,930 --> 00:21:17,110
oxidation event here which is when santa

611
00:21:20,730 --> 00:21:18,940
bacteria are thought to have driven or

612
00:21:22,860 --> 00:21:20,740
been part of the driving mechanism of

613
00:21:24,690 --> 00:21:22,870

oxygenating the earth initially but

614
00:21:27,750 --> 00:21:24,700
almost that at least as interesting to

615
00:21:29,399 --> 00:21:27,760
me is the secondary rise of oxygen here

616
00:21:32,039 --> 00:21:29,409
at this period where oxygen goes from

617
00:21:34,230 --> 00:21:32,049
maybe about one percent up to starts to

618
00:21:35,490 --> 00:21:34,240
rise up towards modern levels and that's

619
00:21:38,850 --> 00:21:35,500
exactly around the time that these

620
00:21:40,320 --> 00:21:38,860
marine vintages start to emerge the

621
00:21:42,180 --> 00:21:40,330
question then is what can these lineages

622
00:21:44,370 --> 00:21:42,190
teach us about the oxygenation of earth

623
00:21:47,519 --> 00:21:44,380
beyond just increasing standing stock of

624
00:21:49,169 --> 00:21:47,529
organic carbon and to think about this

625
00:21:51,269 --> 00:21:49,179
it's useful to kind of briefly review

626
00:21:53,519 --> 00:21:51,279
what we know about ocean chemistry at

627
00:21:55,529 --> 00:21:53,529
that time I should say this is very hard

628
00:21:57,360 --> 00:21:55,539
to study and this is very hotly debated

629
00:21:59,730 --> 00:21:57,370
still but there appears to be at least

630
00:22:02,820 --> 00:21:59,740
some consensus that in the deep open

631
00:22:05,010 --> 00:22:02,830
oceans the at least the the deeper part

632
00:22:06,200 --> 00:22:05,020
of the water column remained anoxic well

633
00:22:08,940 --> 00:22:06,210
after the goe

634
00:22:11,430 --> 00:22:08,950
dominated by iron two-plus and may be

635
00:22:12,560 --> 00:22:11,440
sort of at these continental margins

636
00:22:14,909 --> 00:22:12,570
where there was higher productivity

637
00:22:17,010 --> 00:22:14,919
maybe there there was what's known as

638
00:22:19,409 --> 00:22:17,020

you zinnia driving abundant to sulfide

639
00:22:20,070 --> 00:22:19,419
ions and and whereas you know in the

640
00:22:22,730 --> 00:22:20,080
modern water

641
00:22:24,560 --> 00:22:22,740
modern oceans they're largely

642
00:22:26,149 --> 00:22:24,570
and so the question is what controls his

643
00:22:28,789 --> 00:22:26,159
transition people have suggested several

644
00:22:30,320 --> 00:22:28,799
different negative feedbacks one is that

645
00:22:32,840 --> 00:22:30,330
the sulfide ions can react with

646
00:22:34,370 --> 00:22:32,850
molybdenum and sort of like because

647
00:22:36,380 --> 00:22:34,380
molybdenum has a central role in much of

648
00:22:38,120 --> 00:22:36,390
the nitrogen cycle can potentially

649
00:22:40,190 --> 00:22:38,130
impose some kind of nitrogen limitation

650
00:22:41,539 --> 00:22:40,200
on ocean primary productivity other

651
00:22:44,060 --> 00:22:41,549
people have talked about how iron

652
00:22:45,799 --> 00:22:44,070
two-plus can react with phosphate as a

653
00:22:47,299 --> 00:22:45,809
sort of a grip on the phosphate imposing

654
00:22:49,820 --> 00:22:47,309
phosphorus limitation on the ocean

655
00:22:51,500 --> 00:22:49,830
biosphere but the point is to get over

656
00:22:53,990 --> 00:22:51,510
both of those negative feedbacks you

657
00:22:56,360 --> 00:22:54,000
need to oxygenate the system right so to

658
00:22:57,590 --> 00:22:56,370
oxygenate you have to oxygenate which is

659
00:22:59,450 --> 00:22:57,600
kind of a hard thing to think about and

660
00:23:01,310 --> 00:22:59,460
so people have often argued or thought

661
00:23:03,470 --> 00:23:01,320
about what kind of perturbations might

662
00:23:04,370 --> 00:23:03,480
allow you to get past that system but

663
00:23:06,139 --> 00:23:04,380

what I like to think about is whether

664
00:23:07,430 --> 00:23:06,149
there are other feedback loops that may

665
00:23:10,070 --> 00:23:07,440
allow us to think about this in a more

666
00:23:12,110 --> 00:23:10,080
deterministic way and what I'd like to

667
00:23:14,750 --> 00:23:12,120
what I would like to pose is that iron

668
00:23:16,279 --> 00:23:14,760
actually provides such a mechanism and

669
00:23:19,190 --> 00:23:16,289
the way to think about this is that you

670
00:23:21,610 --> 00:23:19,200
know after the this period in Earth

671
00:23:23,990 --> 00:23:21,620
history you start to see that indeed

672
00:23:26,120 --> 00:23:24,000
molybdenum and phosphorus start to rise

673
00:23:28,190 --> 00:23:26,130
in the ocean the concentration start to

674
00:23:31,490 --> 00:23:28,200
rise which is good for primary

675
00:23:32,720 --> 00:23:31,500
productivity but iron actually drops by

676
00:23:34,340 --> 00:23:32,730
a few orders of magnitude and that's

677
00:23:36,919 --> 00:23:34,350
actually a problem because iron is

678
00:23:38,360 --> 00:23:36,929
central to photosynthesis right so if

679
00:23:39,919 --> 00:23:38,370
you are a forest that excel you have to

680
00:23:41,690 --> 00:23:39,929
figure out a way first to deal with a

681
00:23:43,519 --> 00:23:41,700
drop in iron before you can do

682
00:23:46,310 --> 00:23:43,529
photosynthesis in that dropped iron

683
00:23:49,009 --> 00:23:46,320
environment so to say that another way I

684
00:23:50,930 --> 00:23:49,019
think that ancestral oxygen like

685
00:23:54,320 --> 00:23:50,940
photosynthesis in the air Li has within

686
00:23:56,600 --> 00:23:54,330
it itself negative feedback loop where

687
00:23:58,759 --> 00:23:56,610
you know this is photosynthetic process

688
00:23:59,990 --> 00:23:58,769

here depends on iron and therefore

689
00:24:02,299 --> 00:24:00,000
depends on a flux of iron into the

690
00:24:03,289 --> 00:24:02,309
system but it produces a fox of oxygen

691
00:24:05,690 --> 00:24:03,299
which which sort of ends up

692
00:24:06,830 --> 00:24:05,700
extinguishing this flux of iron here so

693
00:24:08,629 --> 00:24:06,840
you have to figure out a way to deal

694
00:24:10,070 --> 00:24:08,639
with this negative feedback loop and if

695
00:24:11,779 --> 00:24:10,080
you look at what extent phytoplankton

696
00:24:14,029 --> 00:24:11,789
doing prochlorococcus do they do several

697
00:24:16,009 --> 00:24:14,039
things one is that they modify the

698
00:24:18,379 --> 00:24:16,019
stoichiometry of the system to minimize

699
00:24:19,940 --> 00:24:18,389
the usage of iron and what they do is

700
00:24:21,799 --> 00:24:19,950
also these they enhance the absorption

701
00:24:23,509 --> 00:24:21,809
cross section of these systems to make

702
00:24:25,639 --> 00:24:23,519
it more efficient which allows more

703
00:24:27,379 --> 00:24:25,649
oxygen production with less iron but the

704
00:24:29,029 --> 00:24:27,389
other thing that it does is that in the

705
00:24:30,590 --> 00:24:29,039
ocean today iron is actually not free

706
00:24:33,139 --> 00:24:30,600
it's bound to dissolved organic carbon

707
00:24:34,700 --> 00:24:33,149
which is exactly this and in fact the

708
00:24:35,690 --> 00:24:34,710
sorts of molecules that are being

709
00:24:38,919 --> 00:24:35,700
produced by

710
00:24:41,240 --> 00:24:38,929
our caucus these carboxylic acids so

711
00:24:42,649 --> 00:24:41,250
what you then have is within the

712
00:24:44,810 --> 00:24:42,659
metabolic evolution that we're sort of

713
00:24:47,269 --> 00:24:44,820

seeing in prochlorococcus is built in

714
00:24:48,830 --> 00:24:47,279
now a positive feedback loop where the

715
00:24:50,570 --> 00:24:48,840
increase of energy flow through the

716
00:24:53,000 --> 00:24:50,580
system is producing as a by-product

717
00:24:54,740 --> 00:24:53,010
these ligands which can bind iron and

718
00:24:56,419 --> 00:24:54,750
enhance their solubility and

719
00:24:58,940 --> 00:24:56,429
accessibility within this oxygenated

720
00:25:00,620 --> 00:24:58,950
environment and moreover this positive

721
00:25:02,690 --> 00:25:00,630
feedback loop is related to metabolic

722
00:25:04,669 --> 00:25:02,700
rate so as the energy flow as the

723
00:25:07,039 --> 00:25:04,679
metabolic rate increases this positive

724
00:25:08,960 --> 00:25:07,049
feedback loop gets strengthened and you

725
00:25:11,659 --> 00:25:08,970
can over help increasing you start to

726
00:25:13,100 --> 00:25:11,669
overcome this negative feedback loop so

727
00:25:15,259 --> 00:25:13,110
summarize then kind of you have these

728
00:25:17,480 --> 00:25:15,269
phytoplankton here which produce the OC

729
00:25:19,190 --> 00:25:17,490
which bind the iron to stabilize its

730
00:25:20,870 --> 00:25:19,200
abundance it's actually a secondary

731
00:25:23,450 --> 00:25:20,880
thing which is that those same iron

732
00:25:25,430 --> 00:25:23,460
ligands are known to be able to in other

733
00:25:27,919 --> 00:25:25,440
systems able to dissolve rock minerals

734
00:25:30,710 --> 00:25:27,929
and make iron and phosphorus accessible

735
00:25:32,120 --> 00:25:30,720
to life and if you look at where iron

736
00:25:35,750 --> 00:25:32,130
and phosphorous come from out in the

737
00:25:39,080 --> 00:25:35,760
deep open ocean with windblown dust is a

738
00:25:40,490 --> 00:25:39,090

major source of iron and phosphorus and

739
00:25:43,310 --> 00:25:40,500
so if you have this system here which is

740
00:25:45,740 --> 00:25:43,320
producing this excess DLC to stabilize

741
00:25:47,450 --> 00:25:45,750
iron it may not be able to just increase

742
00:25:49,340 --> 00:25:47,460
the accessibility that iron may actually

743
00:25:52,370 --> 00:25:49,350
be able to increase the supply of iron

744
00:25:54,950 --> 00:25:52,380
and phosphorous to the open ocean and of

745
00:25:57,019 --> 00:25:54,960
course at the same time as oxygenation

746
00:25:58,370 --> 00:25:57,029
proceeds those negative feedback loops

747
00:26:00,620 --> 00:25:58,380
that I was talking about before start to

748
00:26:01,730 --> 00:26:00,630
fall away and so the grip of iron even

749
00:26:02,840 --> 00:26:01,740
though you're increasing relatively

750
00:26:03,610 --> 00:26:02,850
speaking the abundance of iron it's

751
00:26:06,289 --> 00:26:03,620
still dropping

752
00:26:07,879 --> 00:26:06,299
allowing it to phosphorus to escape the

753
00:26:11,029 --> 00:26:07,889
grip of iron and increase in total

754
00:26:12,169 --> 00:26:11,039
abundance there's an additional thing

755
00:26:13,879 --> 00:26:12,179
here which is that the sort of

756
00:26:15,259 --> 00:26:13,889
conditions that are being promoted here

757
00:26:17,840 --> 00:26:15,269
which is this dynamic in which you're

758
00:26:19,490 --> 00:26:17,850
drawing down the nitrogen but you're

759
00:26:21,500 --> 00:26:19,500
increasing the bioavailability of

760
00:26:23,600 --> 00:26:21,510
phosphorus sorry of iron and

761
00:26:26,029 --> 00:26:23,610
specifically those are conditions that

762
00:26:28,070 --> 00:26:26,039
are favorable for nitrogen fixation high

763
00:26:29,720 --> 00:26:28,080

iron low nitrogen conditions are where

764
00:26:31,580 --> 00:26:29,730
you generally tend to see nitrogen

765
00:26:34,100 --> 00:26:31,590
fixation and so it's rather interesting

766
00:26:35,779 --> 00:26:34,110
that molecular clocks suggest that the

767
00:26:37,700 --> 00:26:35,789
planktonic cyanobacteria that you see

768
00:26:39,649 --> 00:26:37,710
out in the open ocean emerge right

769
00:26:42,500 --> 00:26:39,659
around at the same time that the open

770
00:26:43,940 --> 00:26:42,510
ocean sign of bacteria do so what this

771
00:26:45,649 --> 00:26:43,950
is then is sort of implying is that

772
00:26:47,180 --> 00:26:45,659
potentially the evolution and the

773
00:26:49,580 --> 00:26:47,190
expansion of these santé material out

774
00:26:51,230 --> 00:26:49,590
into the deep open ocean

775
00:26:53,000 --> 00:26:51,240
brought with it an increased supply of

776
00:26:54,799 --> 00:26:53,010
iron phosphorus and nitrogen out into

777
00:26:59,210 --> 00:26:54,809
the deep open ocean stimulating total

778
00:27:00,740 --> 00:26:59,220
ocean ecosystem productivity now if some

779
00:27:03,049 --> 00:27:00,750
of this sounds familiar to some people

780
00:27:04,850 --> 00:27:03,059
in the audience here it's because people

781
00:27:06,710 --> 00:27:04,860
have actually suggested very similar

782
00:27:09,370 --> 00:27:06,720
mechanisms for what plants did when they

783
00:27:11,870 --> 00:27:09,380
colonize the continents when plants

784
00:27:14,419 --> 00:27:11,880
experience a night of nutrient

785
00:27:16,880 --> 00:27:14,429
limitation they will excrete dissolved

786
00:27:18,560 --> 00:27:16,890
organic carbon from their roots which

787
00:27:20,810 --> 00:27:18,570
dissolves the rocks and releases iron

788
00:27:22,940 --> 00:27:20,820

and phosphorus to become accessible to

789
00:27:25,610 --> 00:27:22,950
those plants also stimulating nitrogen

790
00:27:27,649 --> 00:27:25,620
fixation in their roots and this you

791
00:27:29,240 --> 00:27:27,659
know is was argued to be a key part of

792
00:27:32,029 --> 00:27:29,250
what allowed these systems to expand

793
00:27:34,669 --> 00:27:32,039
onto land increasing the standing stock

794
00:27:37,850 --> 00:27:34,679
of carbon on land and in that process

795
00:27:39,260 --> 00:27:37,860
driving oxygenation and what I guess all

796
00:27:41,539 --> 00:27:39,270
I'm basically trying to say then is that

797
00:27:42,889 --> 00:27:41,549
you can you can argue a very similar

798
00:27:44,690 --> 00:27:42,899
kind of mechanism to what people have

799
00:27:46,340 --> 00:27:44,700
argued for plants happening out in the

800
00:27:47,990 --> 00:27:46,350
open ocean and this is interesting

801
00:27:50,090 --> 00:27:48,000
because they happen sort of roughly in

802
00:27:51,919 --> 00:27:50,100
similar times in Earth history this is

803
00:27:53,149 --> 00:27:51,929
happening somewhere near the in the

804
00:27:55,700 --> 00:27:53,159
neoproterozoic towards the phanerozoic

805
00:27:57,529 --> 00:27:55,710
boundary starts to switch on this

806
00:27:59,240 --> 00:27:57,539
process starts to happen sometime in the

807
00:28:01,490 --> 00:27:59,250
early planet or zoic which is

808
00:28:02,630 --> 00:28:01,500
interesting because I was just trying to

809
00:28:04,159 --> 00:28:02,640
argue before that if you look at the

810
00:28:06,409 --> 00:28:04,169
metabolism of these systems they look

811
00:28:08,029 --> 00:28:06,419
like convergent evolution breaching the

812
00:28:10,880 --> 00:28:08,039
same kind of organization of their

813
00:28:12,620 --> 00:28:10,890

metabolism and in specifically having a

814
00:28:14,090 --> 00:28:12,630
sort of a high metabolic rate type of

815
00:28:16,340 --> 00:28:14,100
phenotype that is part of this expansion

816
00:28:18,380 --> 00:28:16,350
so it really starts to look then if you

817
00:28:19,460 --> 00:28:18,390
kind of look at this level that what's

818
00:28:21,409 --> 00:28:19,470
going on here is that you have now a

819
00:28:23,899 --> 00:28:21,419
process convergent biogeochemical

820
00:28:25,610 --> 00:28:23,909
evolution where photosynthesis oxygen

821
00:28:27,529 --> 00:28:25,620
'ok photosynthesis is sort of expanding

822
00:28:29,090 --> 00:28:27,539
away from these sort of somewhat

823
00:28:31,159 --> 00:28:29,100
protective environments new your

824
00:28:32,480 --> 00:28:31,169
continental boundaries where nutrient

825
00:28:34,639 --> 00:28:32,490
supplies may be a little bit more easier

826
00:28:36,080 --> 00:28:34,649
in some ways out into the deep open

827
00:28:38,210 --> 00:28:36,090
ocean and out onto the continents where

828
00:28:40,310 --> 00:28:38,220
nutrients are harder to access and that

829
00:28:41,899 --> 00:28:40,320
has a key part to do with why

830
00:28:44,750 --> 00:28:41,909
oxygenation is happening in this time in

831
00:28:46,549 --> 00:28:44,760
Earth history so stepping back then and

832
00:28:47,389 --> 00:28:46,559
looking at this sort of profile of Earth

833
00:28:49,730 --> 00:28:47,399
oxygenation

834
00:28:51,889 --> 00:28:49,740
it becomes very tempting to speculate

835
00:28:53,659 --> 00:28:51,899
that what's going on here is that around

836
00:28:56,480 --> 00:28:53,669
this time is when you see first an

837
00:28:58,610 --> 00:28:56,490
expansion of self damping Center

838
00:29:01,850 --> 00:28:58,620

bacteria in sort of slightly more

839
00:29:03,379 --> 00:29:01,860
protective environments but you know

840
00:29:05,029 --> 00:29:03,389
their self damping in that there's

841
00:29:07,579 --> 00:29:05,039
a limit to how much nutrients they can

842
00:29:10,399 --> 00:29:07,589
access and only as they start to invent

843
00:29:12,709 --> 00:29:10,409
a higher metabolic rate variants and

844
00:29:14,749 --> 00:29:12,719
these sort of higher power forms of

845
00:29:16,159 --> 00:29:14,759
oxygen ik photosynthesis can live expand

846
00:29:18,109 --> 00:29:16,169
away into these sort of harsher

847
00:29:19,699 --> 00:29:18,119
environments increasing the total

848
00:29:22,669 --> 00:29:19,709
standings of organic carbon and driving

849
00:29:26,329 --> 00:29:22,679
earth oxygenation and relating this back

850
00:29:28,369 --> 00:29:26,339
then to complexity also and thinking

851
00:29:29,749 --> 00:29:28,379
about biosphere complexity and thinking

852
00:29:32,419 --> 00:29:29,759
about this in the context of increasing

853
00:29:34,609 --> 00:29:32,429
biospheric energy flux right sort of

854
00:29:35,539 --> 00:29:34,619
around this time is when you sort of you

855
00:29:37,339 --> 00:29:35,549
know a lot of evidence is suggesting

856
00:29:39,979 --> 00:29:37,349
this is when eukaryotes start to come on

857
00:29:41,599 --> 00:29:39,989
the scene whereas after this period here

858
00:29:43,190 --> 00:29:41,609
is when you start to see multicellular

859
00:29:45,499 --> 00:29:43,200
large multicellular organisms start to

860
00:29:48,229 --> 00:29:45,509
come online so again thinking about

861
00:29:50,209 --> 00:29:48,239
increasing coupling the increase in mass

862
00:29:54,139 --> 00:29:50,219
energy and complexity of the biosphere

863
00:29:55,459 --> 00:29:54,149

and so just to end then which I always

864
00:29:56,779 --> 00:29:55,469
think it's kind of fun to think about is

865
00:29:58,039 --> 00:29:56,789
that if you start to think about the

866
00:30:00,529 --> 00:29:58,049
evolution of the biosphere through this

867
00:30:02,389 --> 00:30:00,539
lens it's actually not all that

868
00:30:03,859 --> 00:30:02,399
different from thinking about how human

869
00:30:07,129 --> 00:30:03,869
societies have evolved in the

870
00:30:08,899 --> 00:30:07,139
post-industrial age right so as we have

871
00:30:11,269 --> 00:30:08,909
invented ways of pulling evermore

872
00:30:14,479 --> 00:30:11,279
electrons out of the earth married

873
00:30:17,089 --> 00:30:14,489
electrons or electrons from from plants

874
00:30:20,119 --> 00:30:17,099
and so on we have increased the amount

875
00:30:22,190 --> 00:30:20,129
of artificial nitrogen fixation that we

876
00:30:23,719 --> 00:30:22,200
have been doing we are increasing the

877
00:30:25,999 --> 00:30:23,729
amount of phosphate that we are mining

878
00:30:27,379 --> 00:30:26,009
from our minerals on earth and we are

879
00:30:29,659 --> 00:30:27,389
also increasing the rate at which we are

880
00:30:31,609 --> 00:30:29,669
extracting metals from our planet and at

881
00:30:33,499 --> 00:30:31,619
the same time the energy increases not

882
00:30:34,969 --> 00:30:33,509
just the total energy consumption is not

883
00:30:36,859 --> 00:30:34,979
increasing is not only increasing but

884
00:30:38,419 --> 00:30:36,869
also per person is it increasing and

885
00:30:42,190 --> 00:30:38,429
this is corresponding with the

886
00:30:44,149 --> 00:30:42,200
population boom of our human societies

887
00:30:46,039 --> 00:30:44,159
corresponding with all of that increased

888
00:30:47,419 --> 00:30:46,049

energy flow through the system there's

889
00:30:50,629 --> 00:30:47,429
lots of innovations that are happening

890
00:30:51,739 --> 00:30:50,639
that are driving integration and the

891
00:30:53,509 --> 00:30:51,749
emergence of higher levels of

892
00:30:55,940 --> 00:30:53,519
organization with human societies as

893
00:30:57,649 --> 00:30:55,950
well so economies are ever more

894
00:30:59,810 --> 00:30:57,659
integrated or social structures are

895
00:31:01,399 --> 00:30:59,820
becoming more integrated and our

896
00:31:05,029 --> 00:31:01,409
political structures are becoming more

897
00:31:10,489 --> 00:31:05,039
integrated as well so you know it's sort

898
00:31:11,869 --> 00:31:10,499
of tempting then to think of the rostral

899
00:31:16,430 --> 00:31:11,879
revolution as a kind of a heterotrophic

900
00:31:17,210 --> 00:31:16,440
innovation in Earth history and you know

901
00:31:19,340 --> 00:31:17,220
this is a

902
00:31:21,710 --> 00:31:19,350
then also seen in the composition of the

903
00:31:23,930 --> 00:31:21,720
atmosphere right so you know a lot of

904
00:31:25,399 --> 00:31:23,940
people focus on the increase of co2 in

905
00:31:28,010 --> 00:31:25,409
the atmosphere which you know our

906
00:31:29,510 --> 00:31:28,020
burning of carbon is doing that but

907
00:31:31,820 --> 00:31:29,520
actually at the same time we're drawing

908
00:31:33,409 --> 00:31:31,830
down oxygen right through the burning of

909
00:31:35,330 --> 00:31:33,419
the carbon we're drawing down the oxygen

910
00:31:36,680 --> 00:31:35,340
now this is a very small amount on the

911
00:31:38,270 --> 00:31:36,690
total background of oxygen so you don't

912
00:31:41,480 --> 00:31:38,280
really register it all that much but

913
00:31:43,070 --> 00:31:41,490

nevertheless it's it is going on at the

914
00:31:46,490 --> 00:31:43,080
same time now we're on the verge of a

915
00:31:47,690 --> 00:31:46,500
human autotrophic innovation and sort of

916
00:31:50,120 --> 00:31:47,700
playing around we've been trying to

917
00:31:51,140 --> 00:31:50,130
invent artificial photosynthesis and so

918
00:31:52,520 --> 00:31:51,150
I think it's sort of interesting to

919
00:31:54,500 --> 00:31:52,530
think about what this all means for the

920
00:31:56,270 --> 00:31:54,510
Earth's system long-term this total

921
00:31:59,029 --> 00:31:56,280
increase in energy flux and pumping into

922
00:32:00,860 --> 00:31:59,039
the system what will that do so I'll

923
00:32:03,380 --> 00:32:00,870
leave it there and just put up the

924
00:32:04,580 --> 00:32:03,390
acknowledgments with all the people that

925
00:32:14,060 --> 00:32:04,590
have helped me in all of this and open

926
00:32:22,460 --> 00:32:14,070
it up for questions thank you okay

927
00:32:25,940 --> 00:32:22,470
questions for Reggie Thanks does really

928
00:32:28,149 --> 00:32:25,950
interesting talk I really like this idea

929
00:32:30,560 --> 00:32:28,159
of ecosystems being self amplifying

930
00:32:33,590 --> 00:32:30,570
self-organizing evolving trying to

931
00:32:36,380 --> 00:32:33,600
maximize like making more energetic

932
00:32:37,820 --> 00:32:36,390
biosphere have you thought about what

933
00:32:39,010 --> 00:32:37,830
this implies for the emergence of life

934
00:32:41,180 --> 00:32:39,020
on other planets

935
00:32:42,470 --> 00:32:41,190
specifically places like Mars and the

936
00:32:45,169 --> 00:32:42,480
idea that maybe you could have a

937
00:32:46,909 --> 00:32:45,179
biosphere that dies out and what the

938
00:32:49,399 --> 00:32:46,919

energy what that means about the energy

939
00:32:50,930 --> 00:32:49,409
availability on other planets that's

940
00:32:53,120 --> 00:32:50,940
interesting question I have not myself

941
00:32:54,140 --> 00:32:53,130
thought about that very much but that is

942
00:32:55,640 --> 00:32:54,150
an interesting question to think about

943
00:32:57,110 --> 00:32:55,650
what are the available energy supplies

944
00:33:01,430 --> 00:32:57,120
and how long do they remain available

945
00:33:03,350 --> 00:33:01,440
yeah and what it implies about what a

946
00:33:05,240 --> 00:33:03,360
biosphere ending might look like yeah

947
00:33:06,980 --> 00:33:05,250
which is something that people

948
00:33:08,299 --> 00:33:06,990
hypothesize could have had a ton Mars

949
00:33:10,220 --> 00:33:08,309
right yeah it's a good it's a good

950
00:33:11,240 --> 00:33:10,230
question I don't have great deep

951
00:33:13,390 --> 00:33:11,250
thoughts about that but it's good

952
00:33:19,799 --> 00:33:13,400
question

953
00:33:24,000 --> 00:33:22,200
that was lovely

954
00:33:25,590 --> 00:33:24,010
my question could become irrelevant

955
00:33:27,149 --> 00:33:25,600
based on this first answer

956
00:33:30,090 --> 00:33:27,159
prochlorococcus don't fix nitrogen

957
00:33:33,060 --> 00:33:30,100
correct right so so how does that fit

958
00:33:35,149 --> 00:33:33,070
into this and and maybe speculating why

959
00:33:39,539 --> 00:33:35,159
they don't fix the intrusion if their

960
00:33:42,210 --> 00:33:39,549
Optima you know right optimizing rates

961
00:33:46,019 --> 00:33:42,220
of production they've got all these free

962
00:33:48,090 --> 00:33:46,029
electrons yeah why not yeah it's a good

963
00:33:50,789 --> 00:33:48,100

question and I can't actually say that I

964
00:33:52,019 --> 00:33:50,799
have a immediately a very good answer to

965
00:33:56,220 --> 00:33:52,029
you but it's kind of interesting that in

966
00:33:58,080 --> 00:33:56,230
general nitrogen fixation and the major

967
00:34:00,899 --> 00:33:58,090
primary productivity are off are often

968
00:34:03,509 --> 00:34:00,909
separate processes same on on land right

969
00:34:05,279 --> 00:34:03,519
like they're plants do this this you

970
00:34:07,799 --> 00:34:05,289
computation but it's then the microbes

971
00:34:10,530 --> 00:34:07,809
in their roots that are doing the

972
00:34:11,639 --> 00:34:10,540
nitrogen fixation I don't know I think

973
00:34:14,310 --> 00:34:11,649
it might have something to do with

974
00:34:16,409 --> 00:34:14,320
specialization and optimizing of the

975
00:34:19,290 --> 00:34:16,419
relative supply do you need obtuse it of

976
00:34:21,659 --> 00:34:19,300
the two things and how the the problem

977
00:34:23,940 --> 00:34:21,669
is an ecosystem perhaps better solved by

978
00:34:25,740 --> 00:34:23,950
having more abundant of your primary

979
00:34:27,720 --> 00:34:25,750
producers and a slightly lower abundance

980
00:34:29,159 --> 00:34:27,730
of your nitrogen fixers and that's sort

981
00:34:31,290 --> 00:34:29,169
of like a slight more optimal solution

982
00:34:32,579 --> 00:34:31,300
in that sense but but it's great I

983
00:34:34,950 --> 00:34:32,589
haven't really like thought that through

984
00:34:36,869 --> 00:34:34,960
with at the molecular sort of network

985
00:34:39,359 --> 00:34:36,879
level how those trade-offs would come

986
00:34:41,550 --> 00:34:39,369
into play but it is interesting that you

987
00:34:43,470 --> 00:34:41,560
know the two cysts the two groups are

988
00:34:45,599 --> 00:34:43,480

expanding into the open ocean sort of

989
00:34:47,430 --> 00:34:45,609
like kind of in the same timeframe so

990
00:34:48,990 --> 00:34:47,440
looking at that more closely and looking

991
00:34:50,820 --> 00:34:49,000
at their metabolic networks and that

992
00:34:52,440 --> 00:34:50,830
their distribution so I might be able to

993
00:34:58,770 --> 00:34:52,450
like get a better answer to your

994
00:34:59,460 --> 00:34:58,780
question right so that's kind of what I

995
00:35:01,290 --> 00:34:59,470
was trying to say with the

996
00:35:03,450 --> 00:35:01,300
specialization right so prochlorococcus

997
00:35:05,220 --> 00:35:03,460
fiercely and furiously trying to

998
00:35:08,280 --> 00:35:05,230
optimize the acquisition of nutrients

999
00:35:10,020 --> 00:35:08,290
and somehow if you draw the nitrogen

1000
00:35:12,120 --> 00:35:10,030
down to the lowest possible level and

1001
00:35:13,650 --> 00:35:12,130
you're best at that that that means that

1002
00:35:16,470 --> 00:35:13,660
ultimately the ecosystem will supply the

1003
00:35:18,150 --> 00:35:16,480
nitrogen to you right so the other other

1004
00:35:20,040 --> 00:35:18,160
cells will be doing the Nitro fixation

1005
00:35:27,870 --> 00:35:20,050
and eventually it'll make its way back

1006
00:35:40,030 --> 00:35:37,270
yes for the for the second oxygenation

1007
00:35:42,010 --> 00:35:40,040
event yeah the one and a half billion

1008
00:35:44,200 --> 00:35:42,020
year lag between the first and the

1009
00:35:45,400 --> 00:35:44,210
second is that essentially just waiting

1010
00:35:46,660 --> 00:35:45,410
for the innovation of high-powered

1011
00:35:48,520 --> 00:35:46,670
metabolism to come or do you think there

1012
00:35:50,079 --> 00:35:48,530
was another trigger that drove that

1013
00:35:52,210 --> 00:35:50,089

that's actually a really great question

1014
00:35:55,150 --> 00:35:52,220
and something that I like to think about

1015
00:35:57,309 --> 00:35:55,160
a lot right the question is why is there

1016
00:35:58,540 --> 00:35:57,319
this gap here why does one happen here

1017
00:36:00,520 --> 00:35:58,550
and then why does this happen to you why

1018
00:36:02,859 --> 00:36:00,530
does it happen sooner what what is the

1019
00:36:04,120 --> 00:36:02,869
reason for that so one possibility could

1020
00:36:06,609 --> 00:36:04,130
do that it has to do with the nature of

1021
00:36:09,400 --> 00:36:06,619
innovation and the exploration of you

1022
00:36:11,470 --> 00:36:09,410
know a mutation or landscapes of things

1023
00:36:12,849 --> 00:36:11,480
something along those lines I don't

1024
00:36:15,059 --> 00:36:12,859
actually necessarily think that that's

1025
00:36:17,319 --> 00:36:15,069
the main reason I think there are

1026
00:36:19,740 --> 00:36:17,329
potentially triggers in your system that

1027
00:36:22,030 --> 00:36:19,750
have may have something to do with it so

1028
00:36:23,859 --> 00:36:22,040
but exactly how that works that's a very

1029
00:36:25,329 --> 00:36:23,869
much of an open question and so one

1030
00:36:27,339 --> 00:36:25,339
thing that we need to do is to try to

1031
00:36:29,490 --> 00:36:27,349
like actually resolve the timescales of

1032
00:36:31,270 --> 00:36:29,500
when these these divergences of

1033
00:36:33,490 --> 00:36:31,280
prochlorococcus plus and if your

1034
00:36:34,960 --> 00:36:33,500
partners and subgroups are happening and

1035
00:36:36,250 --> 00:36:34,970
sort of get that finer and try to line

1036
00:36:38,770 --> 00:36:36,260
that up with what's going on in the

1037
00:36:40,120 --> 00:36:38,780
earth system at that time but there's a

1038
00:36:42,120 --> 00:36:40,130

few other things that are happening in

1039
00:36:44,349 --> 00:36:42,130
the earth system that might provide some

1040
00:36:45,730 --> 00:36:44,359
constraints to where we should be

1041
00:36:48,579 --> 00:36:45,740
looking for an answer one is that

1042
00:36:50,020 --> 00:36:48,589
there's a supercontinent Rodinia that's

1043
00:36:52,750 --> 00:36:50,030
sort of breaking up right around this

1044
00:36:53,920 --> 00:36:52,760
time right and this is so these these

1045
00:36:56,319 --> 00:36:53,930
marine center bacteria are coming from

1046
00:36:58,450 --> 00:36:56,329
freshwater ancestors and the breakup of

1047
00:37:00,790 --> 00:36:58,460
Rodinia is of course greatly expanding

1048
00:37:02,290 --> 00:37:00,800
the sort of coastline space and the

1049
00:37:04,329 --> 00:37:02,300
interface between freshwater marine

1050
00:37:06,460 --> 00:37:04,339
water so it's maybe increasing the the

1051
00:37:08,920 --> 00:37:06,470
probabilities of going from freshwater

1052
00:37:11,230 --> 00:37:08,930
to saltwater environments

1053
00:37:12,760 --> 00:37:11,240
there's also global glaciation events

1054
00:37:14,740 --> 00:37:12,770
that go on in this time in this

1055
00:37:16,480 --> 00:37:14,750
timeframe where it's thought that I sort

1056
00:37:19,270 --> 00:37:16,490
of covers much of the planet if not all

1057
00:37:22,210 --> 00:37:19,280
how does that relate to all of this you

1058
00:37:23,500 --> 00:37:22,220
know is that potentially triggering some

1059
00:37:25,960 --> 00:37:23,510
of these transitions some of these

1060
00:37:27,849 --> 00:37:25,970
evolutionary divergences or is there

1061
00:37:29,800 --> 00:37:27,859
some other causal mechanisms going on

1062
00:37:32,410 --> 00:37:29,810
here so I think by trying to actually

1063
00:37:34,480 --> 00:37:32,420

integrate what we know from geology with

1064
00:37:35,960 --> 00:37:34,490
what we see in the genomic record will

1065
00:37:41,690 --> 00:37:35,970
help us constrain that

1066
00:37:45,320 --> 00:37:41,700
much better I'm interested in the you

1067
00:37:50,900 --> 00:37:45,330
know the oxygenation but the events are

1068
00:37:55,040 --> 00:37:50,910
exotic and if so you said there you know

1069
00:37:58,970 --> 00:37:55,050
the the new more efficient mechanism Evo

1070
00:38:00,680 --> 00:37:58,980
and making a positive feedback but you

1071
00:38:03,440 --> 00:38:00,690
know we geologists said you know before

1072
00:38:07,130 --> 00:38:03,450
the the second rise of oxygen billion

1073
00:38:10,190 --> 00:38:07,140
years is nothing happened right so so my

1074
00:38:13,880 --> 00:38:10,200
question is what do you think prohibited

1075
00:38:16,640 --> 00:38:13,890
the new innovations before the these two

1076
00:38:20,180 --> 00:38:16,650
events I guess then in a way the the

1077
00:38:22,670 --> 00:38:20,190
speculation what prevented the the

1078
00:38:24,050 --> 00:38:22,680
innovation is in a way I think similar

1079
00:38:26,630 --> 00:38:24,060
to what we were just talking about what

1080
00:38:28,220 --> 00:38:26,640
triggered the innovation so it's a good

1081
00:38:30,620 --> 00:38:28,230
question I don't actually have a

1082
00:38:32,300 --> 00:38:30,630
particularly good answer for you but I

1083
00:38:34,430 --> 00:38:32,310
should also mention about you know

1084
00:38:35,839 --> 00:38:34,440
episodic and about oxygen rise this is

1085
00:38:38,089 --> 00:38:35,849
not somehow this sort of like click

1086
00:38:39,740 --> 00:38:38,099
switch is on here right so you see

1087
00:38:41,900 --> 00:38:39,750
actually perturbations in the carbon

1088
00:38:44,060 --> 00:38:41,910

cycle that extend back to about a

1089
00:38:46,220 --> 00:38:44,070
billion years or so before you really

1090
00:38:47,720 --> 00:38:46,230
start to see the rise of oxygen and then

1091
00:38:49,280 --> 00:38:47,730
when oxygen starts to rise it's not like

1092
00:38:51,560 --> 00:38:49,290
it's suddenly at very high levels it's

1093
00:38:53,210 --> 00:38:51,570
you know ever new evidence sort of is

1094
00:38:54,770 --> 00:38:53,220
continuously now suggesting that oxygen

1095
00:38:56,450 --> 00:38:54,780
doesn't really start to rise towards

1096
00:38:58,490 --> 00:38:56,460
moderate levels until actually well

1097
00:38:59,720 --> 00:38:58,500
after this boundary it may be somewhere

1098
00:39:01,310 --> 00:38:59,730
between three and four hundred million

1099
00:39:02,599 --> 00:39:01,320
years or so so really trying to

1100
00:39:05,540 --> 00:39:02,609
understand what are the sequences of

1101
00:39:07,040 --> 00:39:05,550
innovations you know across that whole

1102
00:39:08,660 --> 00:39:07,050
period and how does that relate to

1103
00:39:10,130 --> 00:39:08,670
what's going on in the earth system is a

1104
00:39:11,570 --> 00:39:10,140
much better understanding of how the to

1105
00:39:18,079 --> 00:39:11,580
line up or needed to be able to answer

1106
00:39:20,329 --> 00:39:18,089
that question well thank you very much

1107
00:39:22,310 --> 00:39:20,339
for the talk I'm probably just gonna go

1108
00:39:23,900 --> 00:39:22,320
back to something that you said at the

1109
00:39:26,839 --> 00:39:23,910
very beginning I probably tried to

1110
00:39:29,240 --> 00:39:26,849
capture again towards the end I guess do

1111
00:39:31,220 --> 00:39:29,250
you believe that I mean you talked a lot

1112
00:39:33,589 --> 00:39:31,230
about positive and negative feedbacks

1113
00:39:36,050 --> 00:39:33,599

actually as a possible way of interpret

1114
00:39:37,460 --> 00:39:36,060
well not a possible way as the way of

1115
00:39:40,460 --> 00:39:37,470
interpreting what's going on in

1116
00:39:43,070 --> 00:39:40,470
different phases and yeah you also

1117
00:39:45,290 --> 00:39:43,080
mentioned that you know you were not as

1118
00:39:46,880 --> 00:39:45,300
close to the origins of life as you

1119
00:39:48,690 --> 00:39:46,890
could have being but do you believe that

1120
00:39:50,970 --> 00:39:48,700
there is a chance we could

1121
00:39:53,430 --> 00:39:50,980
be able like to capture like some sort

1122
00:39:55,859 --> 00:39:53,440
of like list of invariant properties

1123
00:39:57,870 --> 00:39:55,869
like related to either positive or

1124
00:40:01,230 --> 00:39:57,880
negative feedback or a combination or

1125
00:40:03,150 --> 00:40:01,240
both double allows us like to go back

1126
00:40:06,599 --> 00:40:03,160
and say well yeah once you find that

1127
00:40:09,150 --> 00:40:06,609
sort of I don't know interaction of

1128
00:40:11,130 --> 00:40:09,160
whatever components we are talking about

1129
00:40:16,710 --> 00:40:11,140
then there is a chance that something

1130
00:40:18,780 --> 00:40:16,720
interesting is emerging yeah so I don't

1131
00:40:20,460 --> 00:40:18,790
know this is you know answering 100 sent

1132
00:40:22,859 --> 00:40:20,470
directly your question but the question

1133
00:40:24,060 --> 00:40:22,869
of trying to look for general principles

1134
00:40:25,230 --> 00:40:24,070
that are coming from what we see in

1135
00:40:28,500 --> 00:40:25,240
evolution and try to think about

1136
00:40:31,500 --> 00:40:28,510
emergence I think you know this this

1137
00:40:34,050 --> 00:40:31,510
might be one place where we can think

1138
00:40:35,640 --> 00:40:34,060

about that right because what I'm what

1139
00:40:37,470 --> 00:40:35,650
I've been trying to say here or what I

1140
00:40:40,050 --> 00:40:37,480
was trying to say here is that this sort

1141
00:40:41,760 --> 00:40:40,060
of excess electrons flowing through the

1142
00:40:44,370 --> 00:40:41,770
system and causing a bill about

1143
00:40:46,290 --> 00:40:44,380
potential essentially that then leads to

1144
00:40:48,000 --> 00:40:46,300
an emergence of a feedback loop between

1145
00:40:50,250 --> 00:40:48,010
autotrophs and heterotrophs

1146
00:40:51,660 --> 00:40:50,260
that sort of like continues that process

1147
00:40:53,040 --> 00:40:51,670
but it's a sort of a higher level of

1148
00:40:56,130 --> 00:40:53,050
organization of that kind of dynamic

1149
00:40:58,440 --> 00:40:56,140
that actually fits in a general sense

1150
00:41:00,000 --> 00:40:58,450
with you know some people like to think

1151
00:41:01,829 --> 00:41:00,010
about the emergence of metabolism in

1152
00:41:03,420 --> 00:41:01,839
very similar ways right where you have

1153
00:41:06,599 --> 00:41:03,430
an autocatalytic

1154
00:41:09,150 --> 00:41:06,609
and a proto metabolism with ever longer

1155
00:41:10,829 --> 00:41:09,160
self amplifying feedback loops that sort

1156
00:41:13,410 --> 00:41:10,839
of like defined overall structure

1157
00:41:15,960 --> 00:41:13,420
metabolism growing out and growing away

1158
00:41:17,730 --> 00:41:15,970
from prebiotic chemistry and so i would

1159
00:41:20,849 --> 00:41:17,740
say that those kinds of thinking fit

1160
00:41:22,319 --> 00:41:20,859
nicely with each other and and actually

1161
00:41:25,200 --> 00:41:22,329
coming back to the discussion about

1162
00:41:27,930 --> 00:41:25,210
autotrophs and heterotrophs well right

1163
00:41:29,280 --> 00:41:27,940

which is in this case you know I'm

1164
00:41:30,599 --> 00:41:29,290
talking about innovations on the

1165
00:41:32,819 --> 00:41:30,609
autotrophic side but also on

1166
00:41:34,440 --> 00:41:32,829
heterotrophic side and those need not

1167
00:41:36,720 --> 00:41:34,450
happen ever concurrently there may be

1168
00:41:38,849 --> 00:41:36,730
delays between them right just as we

1169
00:41:41,520 --> 00:41:38,859
were talking about the emergence of rtca

1170
00:41:42,750 --> 00:41:41,530
and OTC a and harder choking heterotroph

1171
00:41:44,760 --> 00:41:42,760
e and what does how what happened before

1172
00:41:46,890 --> 00:41:44,770
the luca and so on it could very well be

1173
00:41:48,300 --> 00:41:46,900
and in fact i personally like the idea

1174
00:41:51,089 --> 00:41:48,310
that in the evolution of these

1175
00:41:53,190 --> 00:41:51,099
ecosystems and of the biosphere that you

1176
00:41:55,050 --> 00:41:53,200
have lags between autotrophic and

1177
00:41:56,579 --> 00:41:55,060
hydrophobic innovations and that there

1178
00:41:58,260 --> 00:41:56,589
might be some connections between those

1179
00:42:00,450 --> 00:41:58,270
legs and the perturbations that we see

1180
00:42:01,319 --> 00:42:00,460
in the carbon cycle right so you'll see

1181
00:42:03,420 --> 00:42:01,329
periods in the

1182
00:42:05,910 --> 00:42:03,430
carbon cycle where for tens of millions

1183
00:42:10,109 --> 00:42:05,920
of years maybe it sort of looks with a

1184
00:42:12,299 --> 00:42:10,119
plus positive carbon isotope skew and

1185
00:42:13,680 --> 00:42:12,309
then there's a massive perturbation

1186
00:42:16,709 --> 00:42:13,690
towards negative then it goes back to

1187
00:42:18,779 --> 00:42:16,719
positive and so I think it's at least

1188
00:42:20,819 --> 00:42:18,789

interesting to ponder whether there

1189
00:42:22,289 --> 00:42:20,829
could be a role in all of that for

1190
00:42:24,420 --> 00:42:22,299
delays between autotrophic and

1191
00:42:26,249 --> 00:42:24,430
heterotrophic innovations and given that

1192
00:42:28,049 --> 00:42:26,259
in the extant biosphere if that if

1193
00:42:29,789 --> 00:42:28,059
there's any merit to such an idea there

1194
00:42:32,039 --> 00:42:29,799
appeared to be as possible at least to

1195
00:42:33,839 --> 00:42:32,049
have substantial lags in time between

1196
00:42:35,549 --> 00:42:33,849
autotrophic and heterotroph innovations

1197
00:42:37,410 --> 00:42:35,559
that becomes interesting to think about

1198
00:42:39,120 --> 00:42:37,420
then in the context of early eco systems

1199
00:42:40,739 --> 00:42:39,130
and what kind of lag might you have

1200
00:42:42,809 --> 00:42:40,749
between autotrophic and hydrophobic

1201
00:42:44,279 --> 00:42:42,819
innovations and what does that make us

1202
00:42:50,549 --> 00:42:44,289
think about the boundary of the Mucca

1203
00:42:55,380 --> 00:42:50,559
for example hi thanks for the great talk

1204
00:42:57,839 --> 00:42:55,390
so my question is a little bit more on

1205
00:43:00,329 --> 00:42:57,849
the kind of sociological speculative

1206
00:43:02,069 --> 00:43:00,339
sites so in particular about the very

1207
00:43:06,120 --> 00:43:02,079
last part of your talk which I find very

1208
00:43:07,949 --> 00:43:06,130
interesting so yeah we see we've seen

1209
00:43:11,670 --> 00:43:07,959
this very disturbing exponential growth

1210
00:43:14,849 --> 00:43:11,680
in all kinds of sociological and sort of

1211
00:43:22,789 --> 00:43:14,859
economic metrics which of course is not

1212
00:43:26,189 --> 00:43:22,799
sustainable in the long term and and so

1213
00:43:29,249 --> 00:43:26,199

yeah basically if it carries on the

1214
00:43:32,400 --> 00:43:29,259
earth collapses but there is an

1215
00:43:38,779 --> 00:43:32,410
alternative which which we see hints of

1216
00:43:41,430 --> 00:43:38,789
right now and that is if we instead of

1217
00:43:43,289 --> 00:43:41,440
generating tons of entropy from our sort

1218
00:43:47,309 --> 00:43:43,299
of metabolic activity and traveling

1219
00:43:50,640 --> 00:43:47,319
around using fossil fuels etc if instead

1220
00:43:53,039 --> 00:43:50,650
we we get our sort of our enrichment

1221
00:43:57,569 --> 00:43:53,049
from just engaging with digital

1222
00:43:59,999 --> 00:43:57,579
technology if you extrapolate forward

1223
00:44:01,410 --> 00:44:00,009
you have this of dystopian vision where

1224
00:44:03,180 --> 00:44:01,420
in the future you know we're just kind

1225
00:44:05,430 --> 00:44:03,190
of in the matrix we're asleep all the

1226
00:44:07,650 --> 00:44:05,440
time being pumped with whatever

1227
00:44:09,689 --> 00:44:07,660
nutrients we need but we we live our

1228
00:44:13,499 --> 00:44:09,699
lives to the full in some digital world

1229
00:44:15,270 --> 00:44:13,509
because right now we all kind of feed

1230
00:44:17,310 --> 00:44:15,280
off social media and

1231
00:44:19,230 --> 00:44:17,320
social media feeds off content generated

1232
00:44:20,880 --> 00:44:19,240
in the real world but it wouldn't be

1233
00:44:23,370 --> 00:44:20,890
difficult for all that content to be

1234
00:44:24,660 --> 00:44:23,380
generated also in the digital world at

1235
00:44:27,270 --> 00:44:24,670
which point you don't need to engage

1236
00:44:30,390 --> 00:44:27,280
with the real world at all and so this

1237
00:44:32,820 --> 00:44:30,400
so this sort of dire vision on the one

1238
00:44:35,250 --> 00:44:32,830

hand it's kind of it's a bit scary but

1239
00:44:36,900 --> 00:44:35,260
it does solve this I mean the entropy

1240
00:44:38,430 --> 00:44:36,910
produced from just manipulating all

1241
00:44:40,740 --> 00:44:38,440
those bits would probably be less than

1242
00:44:42,330 --> 00:44:40,750
like 10 billion people flying all around

1243
00:44:46,860 --> 00:44:42,340
the world and that kind of thing right

1244
00:44:49,410 --> 00:44:46,870
so so might save planet Earth and it

1245
00:44:56,010 --> 00:44:49,420
might also explain Fermi's paradox did

1246
00:44:57,690 --> 00:44:56,020
so I think as speculation on that end is

1247
00:45:00,330 --> 00:44:57,700
a little bit beyond me to be able to

1248
00:45:02,520 --> 00:45:00,340
judge that but there is an interesting

1249
00:45:04,980 --> 00:45:02,530
point actually coming up coming back to

1250
00:45:08,340 --> 00:45:04,990
what we were just talking about general

1251
00:45:10,800 --> 00:45:08,350
ideas and general principles and you

1252
00:45:12,270 --> 00:45:10,810
know what I was what in a way what I was

1253
00:45:16,020 --> 00:45:12,280
trying to think about or trying to argue

1254
00:45:18,120 --> 00:45:16,030
here and maybe this relates a little bit

1255
00:45:20,130 --> 00:45:18,130
to what you're talking about is these

1256
00:45:22,800 --> 00:45:20,140
higher levels of organization that start

1257
00:45:25,710 --> 00:45:22,810
to emerge and increase metabolic rate at

1258
00:45:27,660 --> 00:45:25,720
the ecosystem level there's actually an

1259
00:45:29,400 --> 00:45:27,670
interesting way to think here about the

1260
00:45:31,740 --> 00:45:29,410
balance between maximizing rate and

1261
00:45:33,900 --> 00:45:31,750
maximizing efficiency mm-hm right so

1262
00:45:35,580 --> 00:45:33,910
overall you're still maximizing rate but

1263
00:45:37,500 --> 00:45:35,590

these innovations that produce higher

1264
00:45:38,990 --> 00:45:37,510
levels of organization are in a way

1265
00:45:41,610 --> 00:45:39,000
increasing the efficiency of the system

1266
00:45:43,140 --> 00:45:41,620
right and so that then drives down the

1267
00:45:45,420 --> 00:45:43,150
amount of waste that you're producing

1268
00:45:47,610 --> 00:45:45,430
and so on and so you know perhaps in

1269
00:45:49,740 --> 00:45:47,620
thinking about human societies things

1270
00:45:51,720 --> 00:45:49,750
like emergence of recycling for example

1271
00:45:54,120 --> 00:45:51,730
would be one example of that but so

1272
00:45:56,610 --> 00:45:54,130
maybe you know our complexification are

1273
00:46:01,380 --> 00:45:56,620
sort of of our social systems maybe that

1274
00:46:03,030 --> 00:46:01,390
increases our efficiency actually all

1275
00:46:08,380 --> 00:46:03,040
right so we're at time so let's thank